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AERODYNAMIC HEATING OF THE LIFTING BODIES

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SUMMARY

Singularities are considered in the heat flow distribution over the surface of vehicles using the aerodynamic lift.

Heat flow maxima may appear on the lower vehicle's surface (attached flow) as a consequence of the large curvature of the edges and on its upper surface in the case of detached flow.

The results are presented of laminar boundary layer calculations and of the experiments in supersonic wind tunnels.

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Among hypersonic flying crafts using the aerodynamic lift there are crafts with low aerodynamic quality ($Q_{max} \approx 2 - 3$) of the carrier body type as well as crafts with high aerodynamic quality ($Q_{max} \approx 5 - 10$) of the airplane type.

If we assume that a drag component, independent of the angle of attack (C_{xo}), is part of the total dynamic forces of the body, while the aerodynamic lift and part of the drag dependent on the angle of attack vary with the latter in the same way as in the case of a flat plate, we may represent the dependence of Q_{max} on C_{xo} and the Mach number M as shown in Figure 1.

It may be seen from Fig.1 that the maximum aerodynamic quality, i.e., $Q_{max} \approx 5 - 10$, may be obtained for $C_{xo} \approx 0.001$ and angles of attack $\alpha \approx 3 - 6°$ that is, only in the case of "thin" aircrafts, sufficiently small "bluntness" radii of the nose cap and edges and of sufficiently small frictional resistance. The lifting "bodies" may also be not thin, with sufficiently large radii of bluntness. The variety of shape assignemencs of hypersonic aircrafts results in substantial differences in magnitude, surface distribution and duration of action of thermal flows, and, by way of consequence, of thermal insulation. The simplest means of this shielding is heat elimination by

(*) Aerodinamicheskoye nagrevaniye nesushchikh tel.

radiation on the condition that the temperature of the lining do not exceed the acceptable figure, in which case the aerodynamic quality maximum may be the condition for the choice of the shape [3].

In conditions of multitude of apparatus' applications, blow in may be applied into the boundary layer of cooling gas for thermal shielding of those areas of its surface on which the heat elimination by radiation is insufficient. This procedure is particularly promising for the nose cones and hypersonic edges of aircrafts; it may also be utilized as means of lowering the frictional resistance. The aerodynamic quality, the heat shielding system, the weight and the shape of the apparatus are all interralated by the condition of optimum satisfaction of its basic requirements. Included in the number of data required for the selection of optimum shapes, are the data on the peculiarities of heat flow distribution. This is precisely the question which is the object of consideration in the present paper.

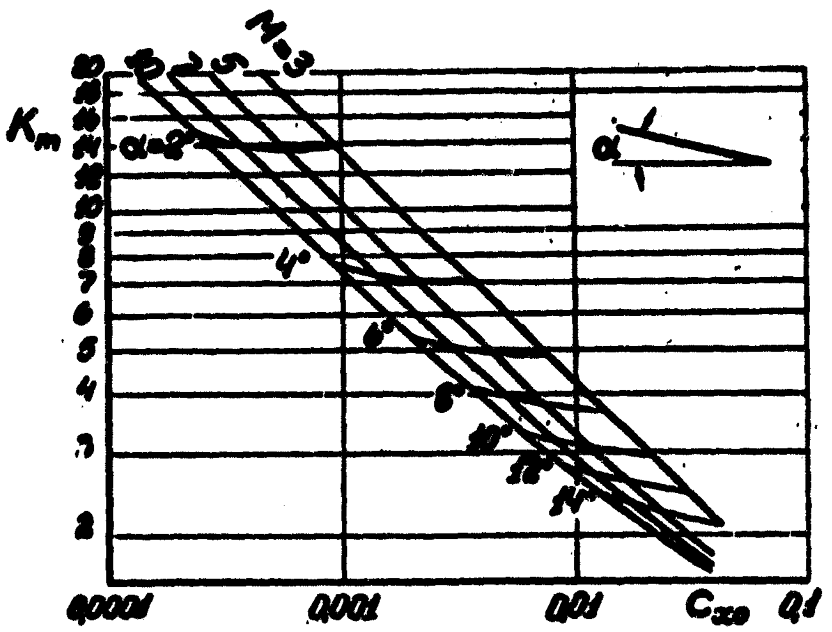

Fig.1. Dependence of aerodynamic quality maximum on the drag for a zero angle of attack α and Mach number M

One of the simplest lifting bodies is the circular cone. In its cross-section the magnitude of thermal flow attains its optimum value on the lower side in the symmetry plane and increases with the angle of attack (see Fig.2). The distribution of the thermal flow along the cross-section of the continuous part of the flow varies little with the change of the angle of cone, of the Mach number and of the angle of attack laminar boundary layer, calculation). A round cone does not ensure a high aerodynamic quality, which can be improved by passage to the elliptical cross-section. Besides, during the passage to

to the elliptical cone, the curvature radius of the cross-section in the symmetry plane increases, which results in a corresponding decrease of the thermal flow (Fig.2). However, lateral edges appear then, whose curvature radius decreases with the increase in ellipse axes' ratio; the ratio of ellipse's curvature radii in the symmetry plane is equal to the cube of axes' ratio. When the axes' ratio e = 3, the decrease of the curvature radius of the edges results in the apperance of thermal flow peaks on the lower side of the ellitpical cone already near the edges (Fig.2) [1].

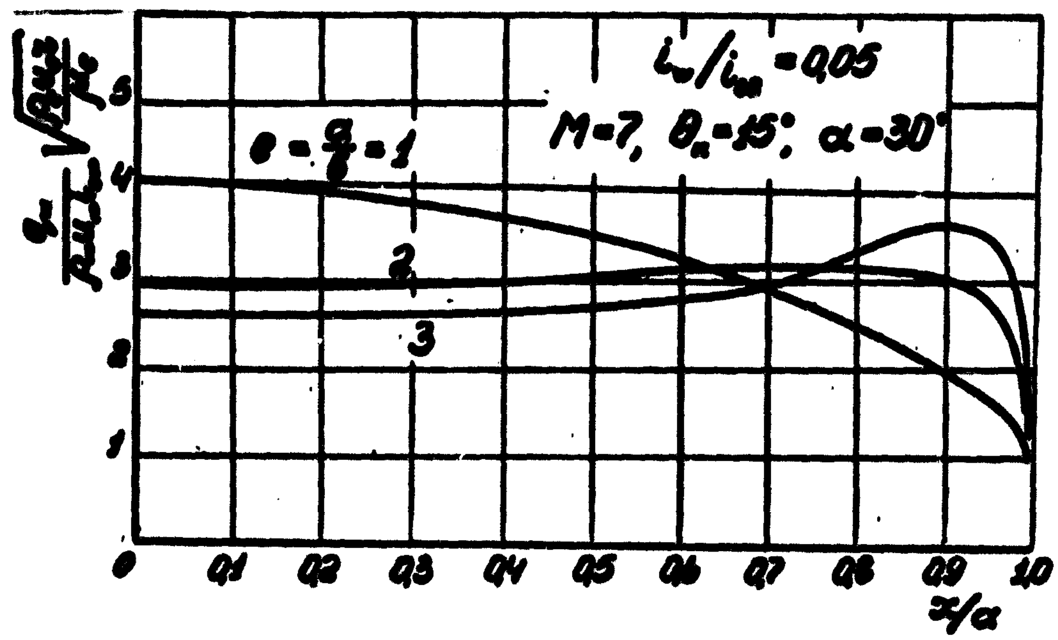

Fig.2 Distribution of the thermal flow along the ross-section of elliptical cone (laminar boundry layer, calculation)

Such an influence of the shape of the cross-section on thermal flow distribution is also confirmed by testing elliptical cone models of identical volume in a shock tube (Fig.3) [4]. The small bluntings of nose cones do not result in substantial variations in the distribution of thermal flow. Thus, if the best possible uniform distribution of the flow in cross-section (lower part) is desirable, the ratio of ellipse's semi-axes must vary, depending upon the angle of attack, from e = 1 for $\alpha = 0$ up to 2 - 3 for $\alpha \sim 90°$.

In the symmetry plane of a delta-wing (plate) the thermal flow rises with the angle of attack and with the decrease of angle at the summit (Fig.4); on edges the thermal flow $\to \infty$ (Fig.5 [1]). At hypersonic velocities sharp edges are possible only at cooling by blowing in; since because of interaction of the head of the wave with the boundary layer the "effective" bluntness radius is then zero, it makes no sense to sharpen the edges, but one should select a geometric bluntness radius from the condition of minimum resistance at the given temperature of the suriace being cooled and the given coolant agent consumption.

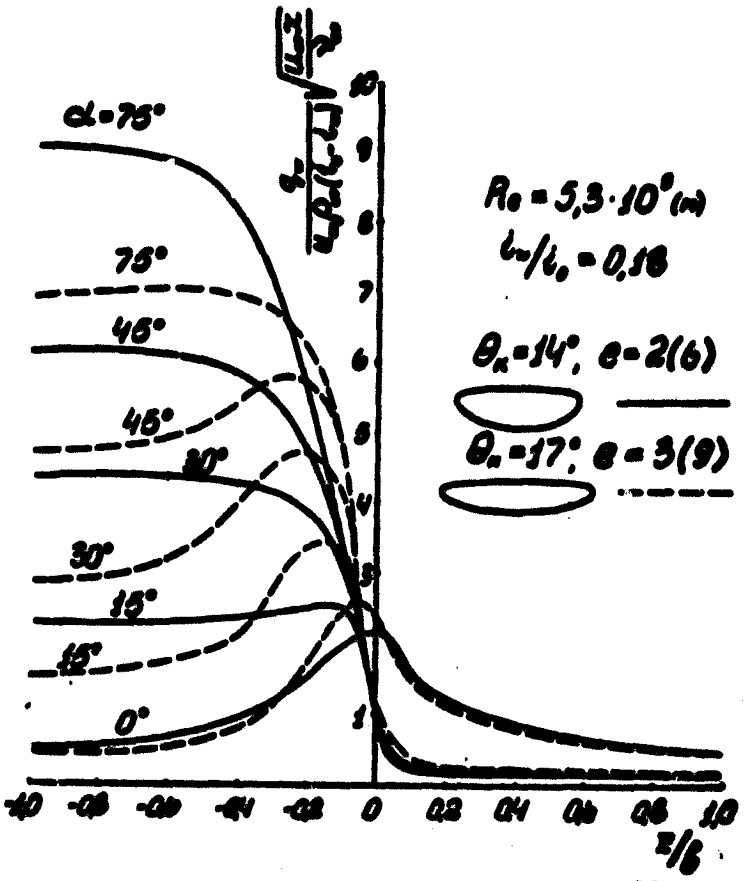

Fig.3. Distribution of thermal flow along the cross-section of an asymmetrical elliptical cone (laminar boundary layer, experiment)

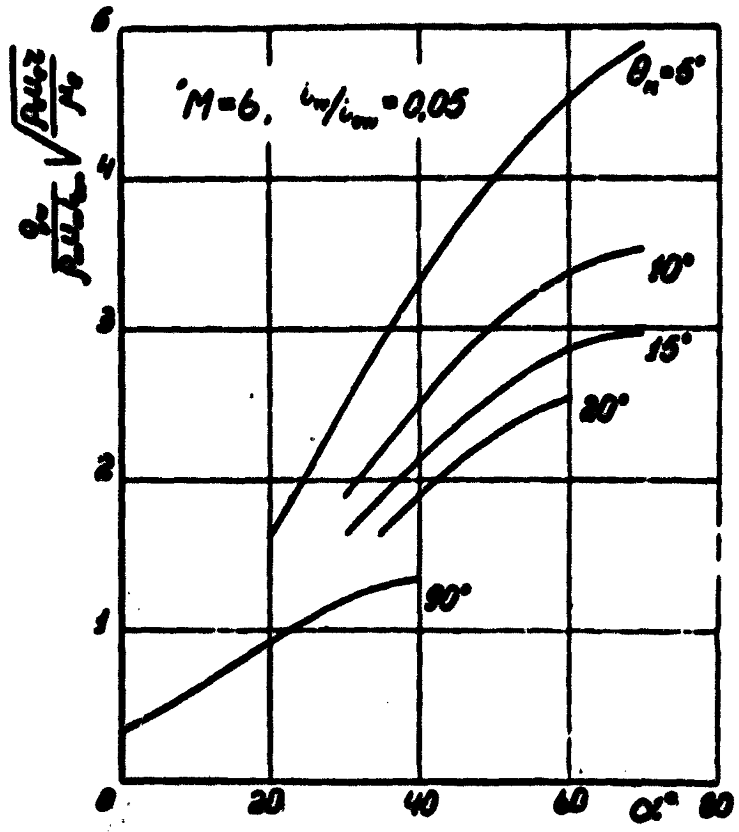

Fig.4. Dependence of thermal flow in the symmetry plane of a triangular plate on the angles of attack and aperture θ_k (laminar boundary layer, calculation)

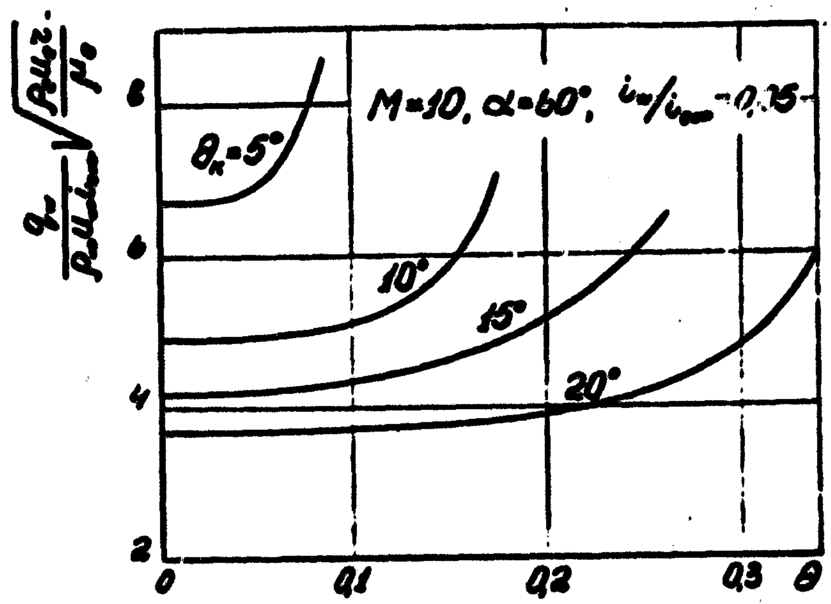

Fig.5. Distribution of thermal flow along the cross-section of a triangular plate (laminar boundary layer, calculation)

The essential singularities of streamline flow past the upper side of the "lifting" body were detected experimentally.[2]. Thus, for instance, for high Mach numbers M, the flow past the plane side of a blunted semi-cone at zero angle of attack is distinct from the flow past a plate: near the edges the flow breaks off, and in the middle it approaches the surface of the semi-cones in the form of two narrow "jets" [Fig.6]. The magnitude of thermal flow was measured with the aid of thermopaint; the white bands (Fig.6) are the regions of color variation at the very beginning of the experiment, that is, the regions of increased thermal flow. The distribution of the latter along two semi-cone cross-sections for various angles of attack is shown in Figure 7. For great angles of attack a thermal flow "peak" appears in the cross-section $\overline{x} = 6.16$ in the symmetry plane.

The thermal flow maxima exceed by one order the magnitude of thermal flow toward a flat plate, which itself is flown about by laminar flows without breaks. The decrease of the Reynolds number R, computed according to the characteristic dimension of bluntness, results in a decrease of thermal flow peaks (Fig.8); for high Mach numbers M and small Reynolds numbers R, they remained thus far generally undetected [4]. The substantial irregularity in the distribution of thermal flow about surfaces hitting the regions where the flow breaks off is a rather general phenomenon. There is always a mixing region of external and break-away flow, in which gas is ejected from the break-away region. If the break-away flow is, as an average, stationary in time, the consumption of ejected gas must somewhere be compensated by inflow into the break-away region originating from the outer flow. At supersonic velocities this usually takes place in the form of "jets flowing into the break-away region from zones of increased pressure behind the shock waves closing the break-away region. The shape of these jets, the depth of their propagation insides the break-away region, depend both on the shape of the body and the numbers M and R; however, if these "jets" reach the surface of the body, an increased thermal flow will take place in these spots, whereupon this increase may take the form of a "peak" characteristic of the regions of torn off flow. Because of flow break off the upper edges, heat flow peaks must also be present on the upper side of the wedge, whereupon they are substantially greater in the case of a blunted leading edge (Fig.9) It is possible that this is linked with the effect of "entropic" vortices on the break-away flow, which are forming at spots of sharp curvature change in the leading shock wave [3]. The "jet" approaches the upper side of the triangular plate with sharp edges in the symmetry plane (Fig.10); this is why the "peak" of thermal flow decreases with the decrease of the Reynolds number R [2] (Fig.11). The rounding off of the leading edge does not result in the total vanishing of thermal flow "peaks" (Figures 12, 13, experiments by I. P. Morozov). In the experiments, whose results are presented above, the boundary layer ahead of the break away was laminar; the possible influence of transition has not been investigated so far.

From the above considerations it is obvious that the distribution of thermal flow about the surface of a "lifting" craft of even the simple form, may substantially differ from the distribution of thermal flow about the surface of ballistic and sliding type. One should also bear in mind that lifting bodies may have different additional parts, such as, aerodynamic guidance organs, protruding superstructures, fractures of edges and so forth, all cases in which

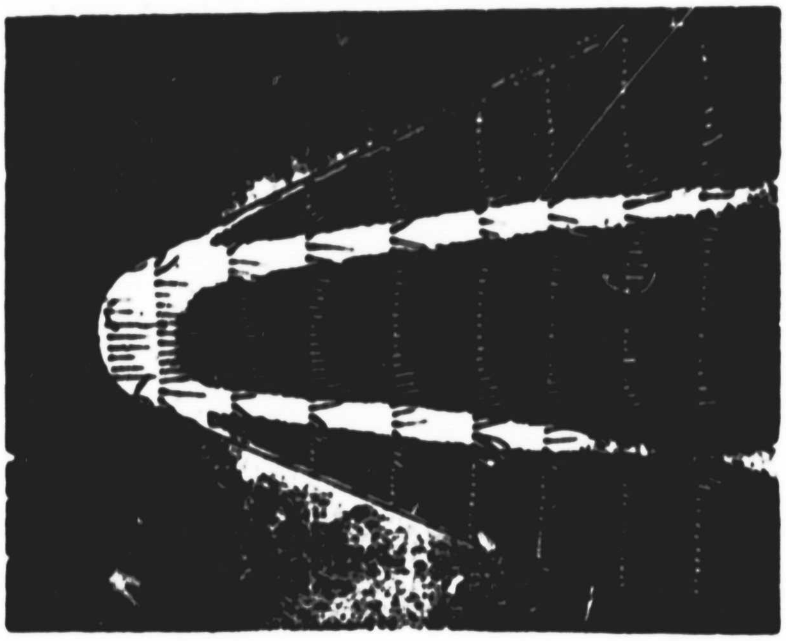

Fig.6

Current boundary lines and color variation of thermopaint on the plane side of the semicone disposed along the flow (M = 5)

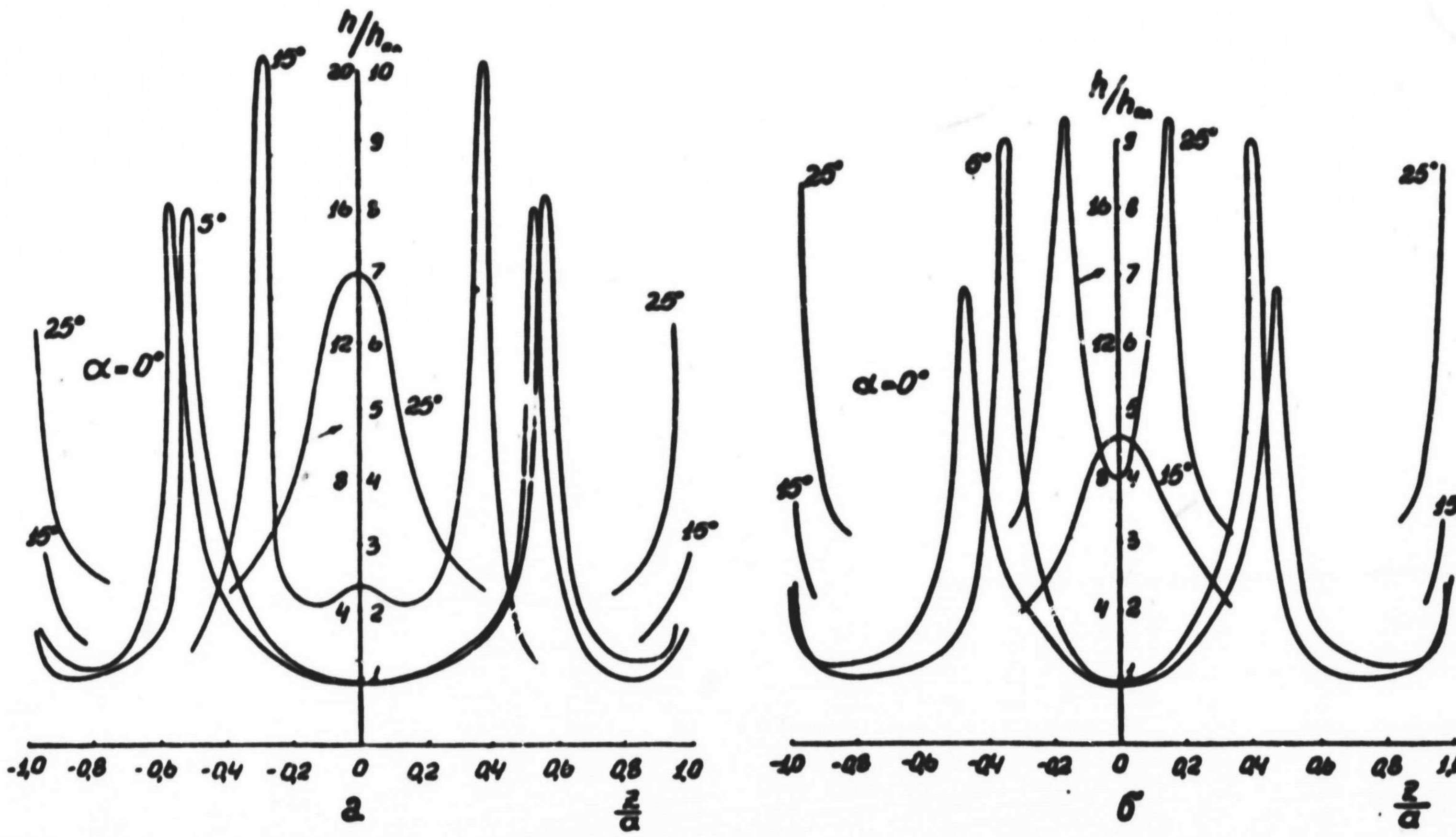

Fig.7. Distribution of thermal flow along the plane side of the semicone (experiment, thermopaint)

(a) $\frac{x}{a} = 3$, (б) $\frac{x}{a} = 6$; $\underline{a}$ is the bluntness radius; M = 5, $R_\infty = 9.5\ 10^6$ (M), $\theta_k = 24°15'$

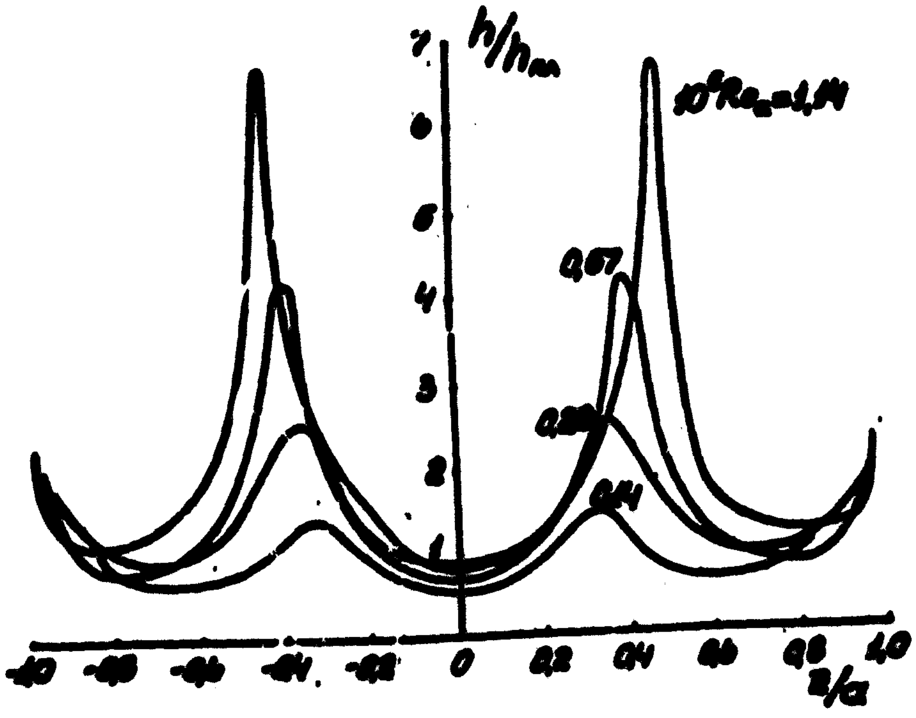

Fig.8. Dependence of the thermal flow on the plane side of the semi-cone on the Reynolds number of bluntness (experiment. thermopaint).

$$\alpha = 0; \quad \frac{x}{a} = 6; \quad \theta_k = 24°15'; \quad M = 5$$

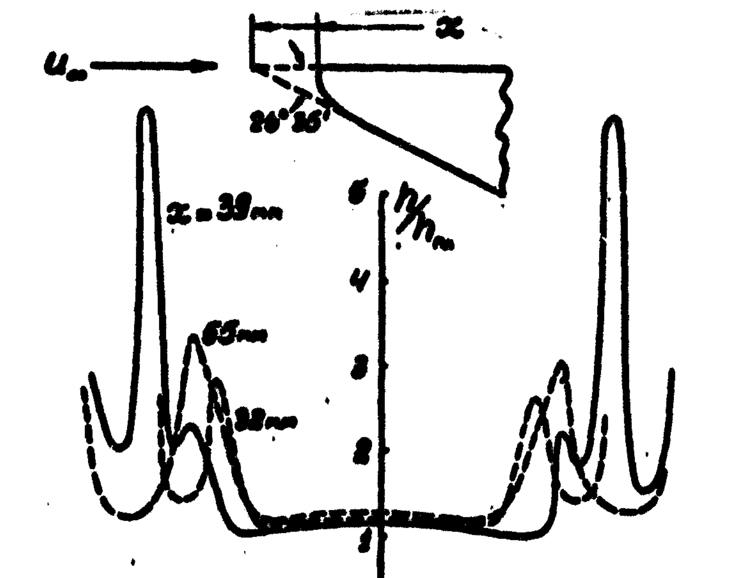

Fig.9. Distribution of the thermal flow along the upper side of the pyramidal wedge (experiment. thermopaint)
$M = 5$; $R_\infty = 9.5 \cdot 10^6$ (M)

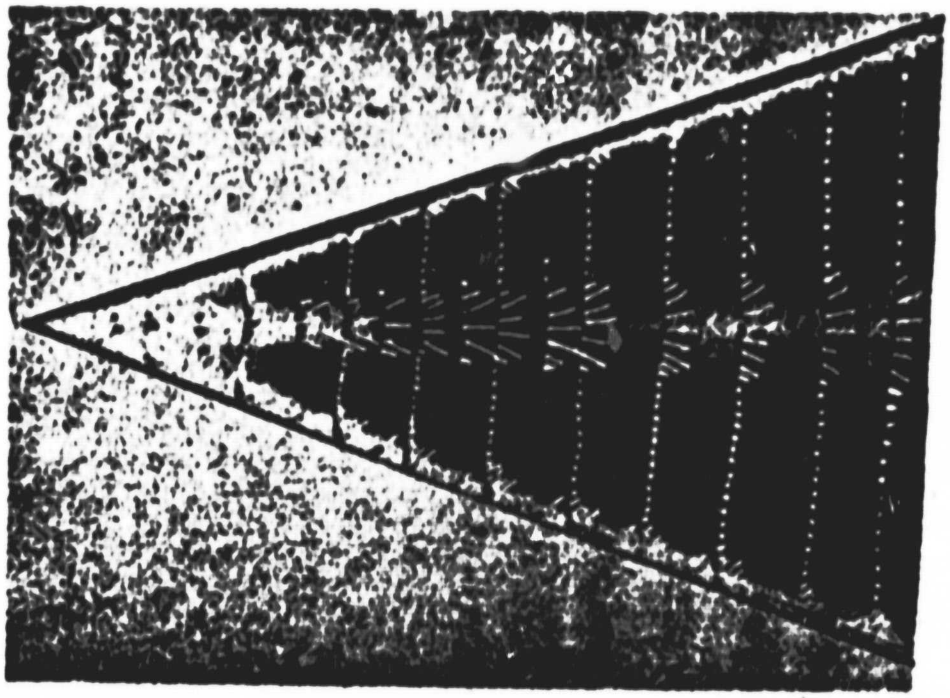

Fig.10. Limiting current lines on the upper side of the triangular plate (M = 5; α = 15°; θ_k = 18°50')

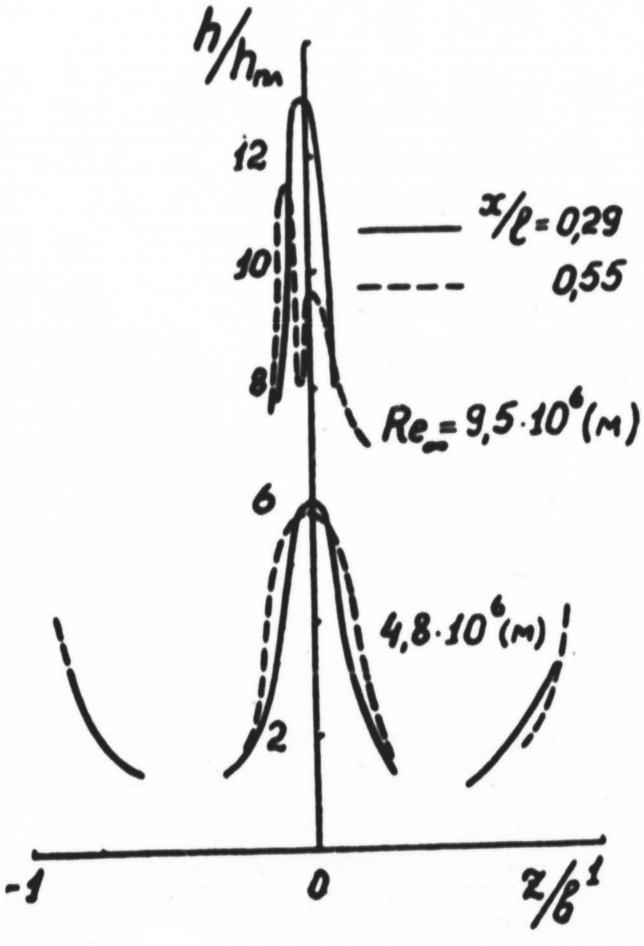

Fig.11. Distribution of thermal flow along the upper side of the triangular plate (experiment, thermopaint) M = 5; α = 15°; θ_k = 18°50')

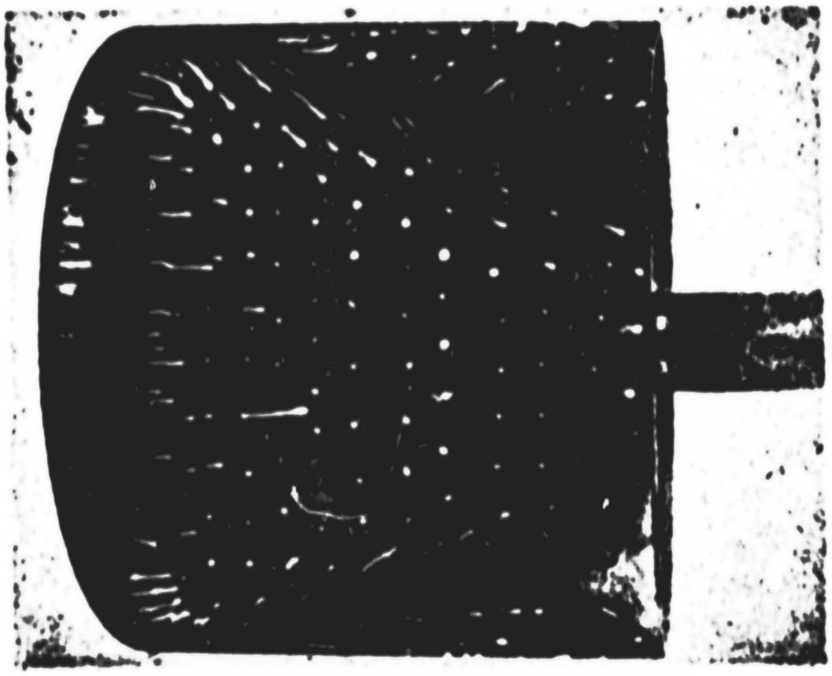

Fig.12

Limiting current lines on the upper side of an elliptical cylinder with a nose part in the shape of a semi-ellipsoid of revolution ($M = 5$; $\alpha = 20°$; $e = 3$).Thermopaint color variation

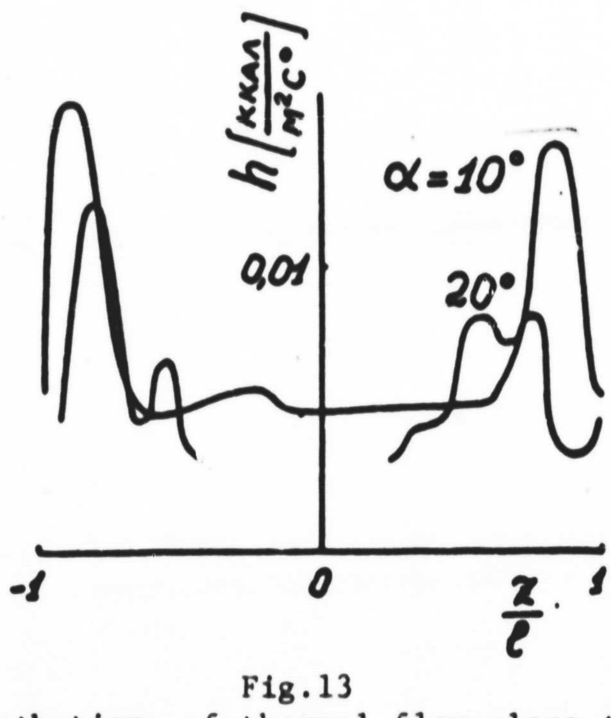

Fig.13

Distribution of thermal flow along the upper part (side) of the elliptical cylinder (experiment, thermopaint; $M = 5$; $\frac{x}{l} = 0.75$)

appearance of "peaks" of thermal flow, linked with the interference of waves with the boundary layer is possible; these cases are similar to those studied in the works [2, 5, 6]. Because of the complexity of thermal flow distribution and condition of multiplicity of applications, one of the probable means of thermal shielding of the region of the surface with great thermal flows is the blowing in of gas from within the apparatus into the boundary layer.

There are still great many difficulties linked with the regulation of coolant consumption depending upon the time and place and also the reliability.

****** T H E E N D ******

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